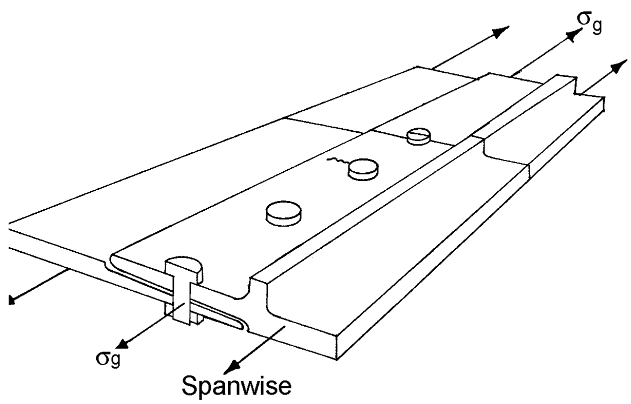
6.4 Multiple Load Path Structure

The basic purpose of the example is to illustrate two facets of damage tolerance design. The first is that, while a structure may appear to fit one category of JSSG-2006 by virtue of its geometry, the loading and damage progression may force the structure to be qualified under another category. Secondarily, this example attempts to illustrate the use of some of the more advanced techniques described in Section 11.

EXAMPLE 6.4.1 Wing Spanwise Splice

Problem Definition

The problem is to determine the adequacy of the base or depot level inspection intervals for an existing cargo aircraft wing structure. The fracture critical location in the wing box has been described as the lower surface spanwise splice. In addition, an attempt will be made to qualify the structure as Multiple Load Path Fail Safe structure per JSSG-2006.



Spanwise Splice, Wing Lower Surface

Material Property Data

Spanwise splice material is 7075-T6511 extrusion

K_{Ic} = 25 ksi $\sqrt{in.}$

K_c = 50 ksi $\sqrt{in.}$

$$\frac{da}{dN} = \frac{2.74x10^{-10}(\Delta K)^{4.0}}{(1-R)50.0-\Delta K}$$ (Forman equation)

Structural Loads and Stress History

Input stresses are defined for a typical usage mission mix of 14 missions consisting of 12 logistics missions and 2 training missions with touch-and-go landings. Typical stresses for logistics and training missions are shown in the following tables. The mission mixes to be considered are:

a) Logistics missions only

b) Training missions only

c) Heavy logistics deliver and lightweight return

d) Mixture of logistics and training missions of typical usage.

Typical Logistics Mission Spectrum

Layer	Maximum Stress (ksi)	Minimum Stress (ksi)	Cycles per Layer
1	14.0	0.0*	1
2	14.0	12.6	325
3	16.0	10.0	32
4	17.6	8.6	2
5	19.3	6.3	1
6	17.6	8.6	2
7	16.0	10.0	32
8	14.0	12.6	325

*Actual minimum GAG stresses were approximately –12.0 ksi (compressive). Negative stresses were truncated to zero for analysis.

Typical Training Mission Spectrum

Layer	Maximum Stress (ksi)	Minimum Stress (ksi)	Cycles per Layer
1	8.0	0.0*	1
2	8.0	7.0	429
3	10.0	6.4	64
4	12.0	4.4	4
5	13.7	2.7	1
6	8.0	7.0	429
7	10.0	6.4	64
8	12.0	4.4	4
9	13.7	2.7	1
10	8.0	0.0*	1
11	8.0	7.0	429
12	10.0	6.4	64
13	12.0	4.4	4
14	13.7	2.7	1
15	8.0	0.0*	1
16	8.0	7.00	429
17	10.0	6.4	64
18	12.0	4.4	4
19	16.1	0.7	1
20	8.0	0.0*	1
22	10.0	6.4	64
23	12.0	4.4	4
24	13.7	2.7	1
25	8.0	7.0	429
26	10.0	6.4	64
27	12.0	4.4	4
28	8.0	0.0*	1
29	8.0	7.0	429
30	10.0	6.4	64
31	12.0	4.4	4

*Actual minimum GAG stresses were approximately –6.0 ksi (compressive). Negative stresses were truncated to zero for analysis.

Initial Flaw Sizes

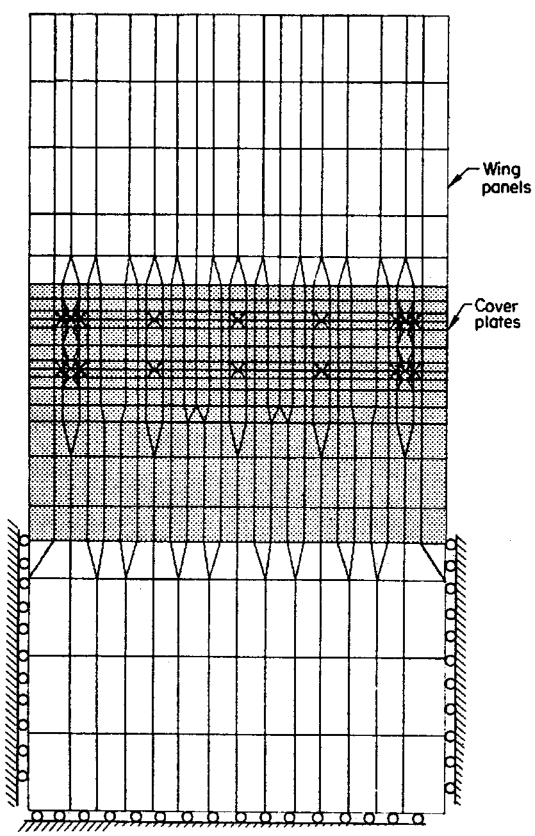
The splice structure is assumed to be a multiple load path structure. It is dependent structure because of assembly drilling of fastener holes. The damage assumptions are:

- Initial - 0.02 inch radius corner crack at edge of hole toward free edge (each plank of splice) for Multiple Load Path Fail Safe qualification,

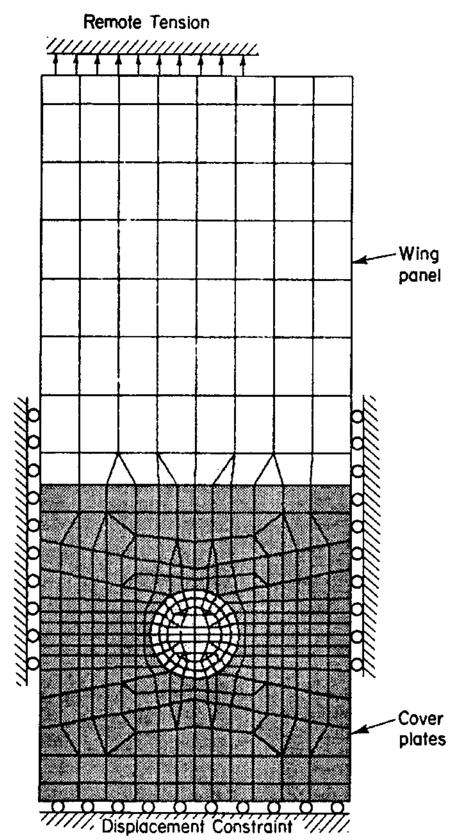
  - 0.05 inch for Slow Crack Growth qualification
- Continuing - 0.005 inch radius corner crack at diametrically opposite side of hole in each plank.

Geometry Model

The finite-element-modeling approach was selected since this type of joint might contain some load transfer. Two levels of finite-element models were developed for the structural splice. The large first level model contains ten fastener holes with fasteners and over-layed grid systems in the reduced splice area which are coupled through the centroid of each fastener. The second level model is a much finer grid model of a section of the first level model. Boundary nodal point and fastener displacements of the first level model were applied to the second level model for fracture mechanics analysis. The contact boundary conditions of the fastener and plate were those of a loose "neat-fit" pin.

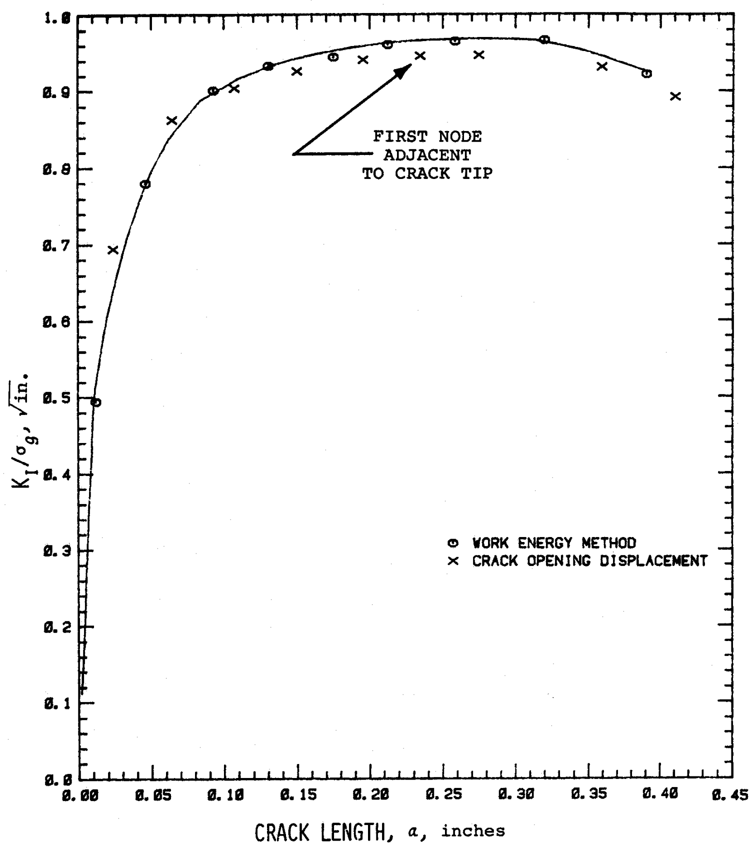


Joint Finite Element Model



Criteria Hole Finite Element Model

The variation of stress-intensity factor (K) with crack size as derived from this analysis is shown in the plot. The work-energy and crack-opening displacement methods show essentially the same results. Details of this type of derivation are covered in Section 11.



Stress Intensity Factor Coefficient as a Function of Crack Size (to Free Edge)

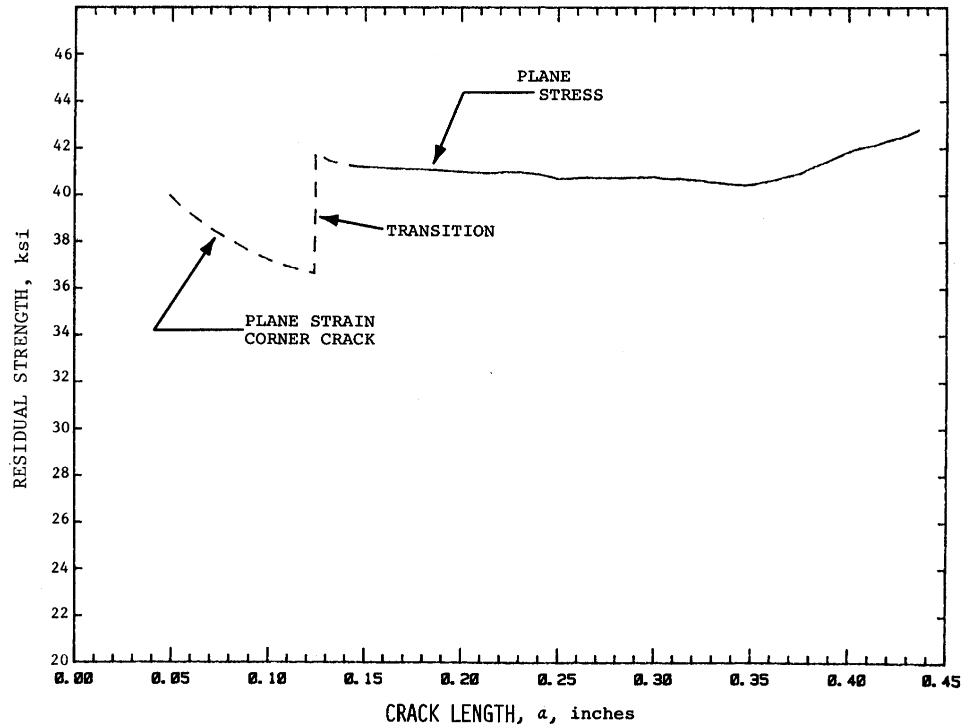
The basic stress analysis of this joint demonstrated that each member of the splice is equally stressed and there was no load transfer. This means that both planks, if cracked, will crack at the same rate and the two planks will become critical at the same time. Therefore, the structure will never meet Multiple Load Path Fail Safe structure requirements and must be analyzed as Slow Crack growth with corresponding initial damage sizes.

Residual Strength Diagram

The residual strength diagram was generated based on the following failure criteria:

- Corner crack instability based on K_{Ic}
- Through-the-thickness crack instability based on K_c

The residual strength in the large crack region is based on a through-the-thickness edge crack. The figure shows the residual strength diagram for the structure based on the above assumptions and the stress-intensity-factor analysis. The limit load stress level is assumed approximately 35 ksi.



Residual Strength Curve of Spanwise Splice

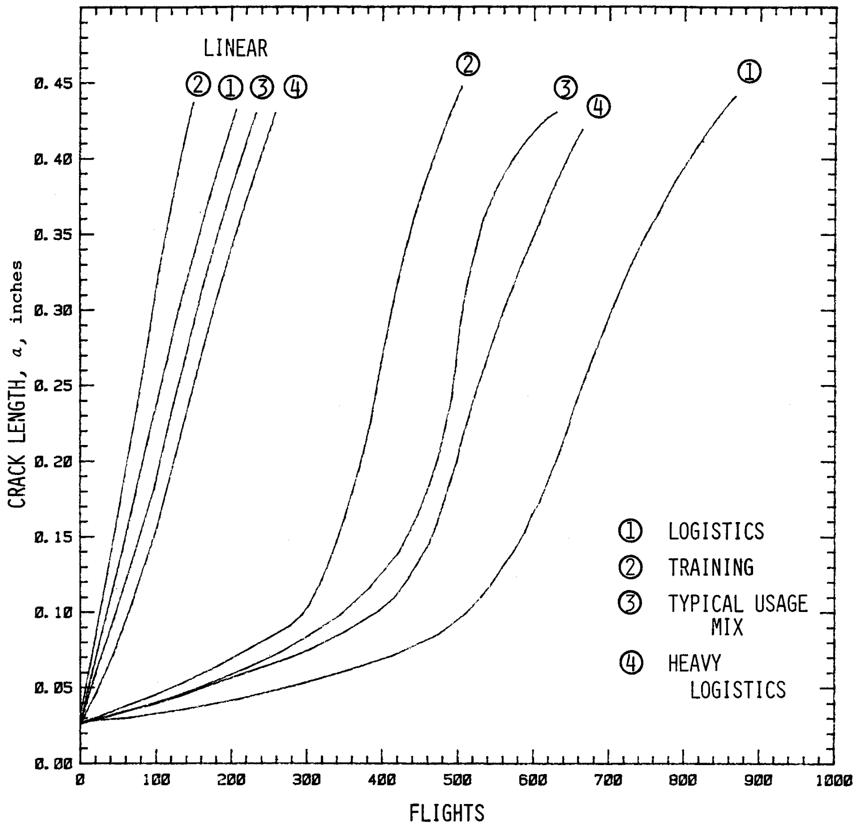
Fatigue Crack Growth Analysis

The spectra used in the growth analysis consisted of the typical usage mix of 14 missions as mentioned previously. The stresses were ordered in a low-high-low sequence per mission. Other missions were logistics only, training only, or heavy logistics only. The mission mixes considered in the analysis were:

- Logistics mission only
- Training mission only
- Logistics and training missions (typical usage)
- Heavy logistics

The next figure shows the fatigue-crack-propagation behavior of the splice subjected to the four mission mix spectra starting from the initial 0.050 inch corner flaw at the edge of the hole.

There are two sets of curves in the figure. The linear curves represent linear solutions that ignore load interaction (retardation) effects. The linear solutions are seen to be conservative by at least a factor of three. Even more significant for life and inspection interval predictions is the fact that, when considering mission mix variations, linear analysis may not even rank the various stress histories correctly. The linear analysis shows the "logistics only" mission to be more severe than the various mission mixes. However, full consideration of load interaction effects shows this to be the most benign of the four variations considered.



Fatigue Crack Propagation Behavior of Spanwise Splice Under Various Spectra

Inspection Intervals

Based on the spectrum loading fatigue-crack-propagation results, the qualification and the required inspection intervals can be determined. The original design life of the structure was 30,000 hours with a quarter life depot or base level inspection interval of 7500 hours.

For qualification as Slow Crack Growth Non-Inspectable structure, the analytical crack-growth life should be 2 lifetimes or 60,000 hours. For qualification as Slow Crack Growth Depot Level Inspectable structure, the crack-growth life from a 0.25 inch in-service flaw to critical should be 1/2 lifetime or 15,000 hours. These requirements cannot be met.

Based on an average training flight of 3.0 hours and an average logistics flight of 4.0 hours, the following inspection intervals could be recommended instead:

Training Missions = 645 hours

Logistics Missions = 1450 hours

Typical Usage Mix = 1875 hours

Heavy Logistics = 1375 hours